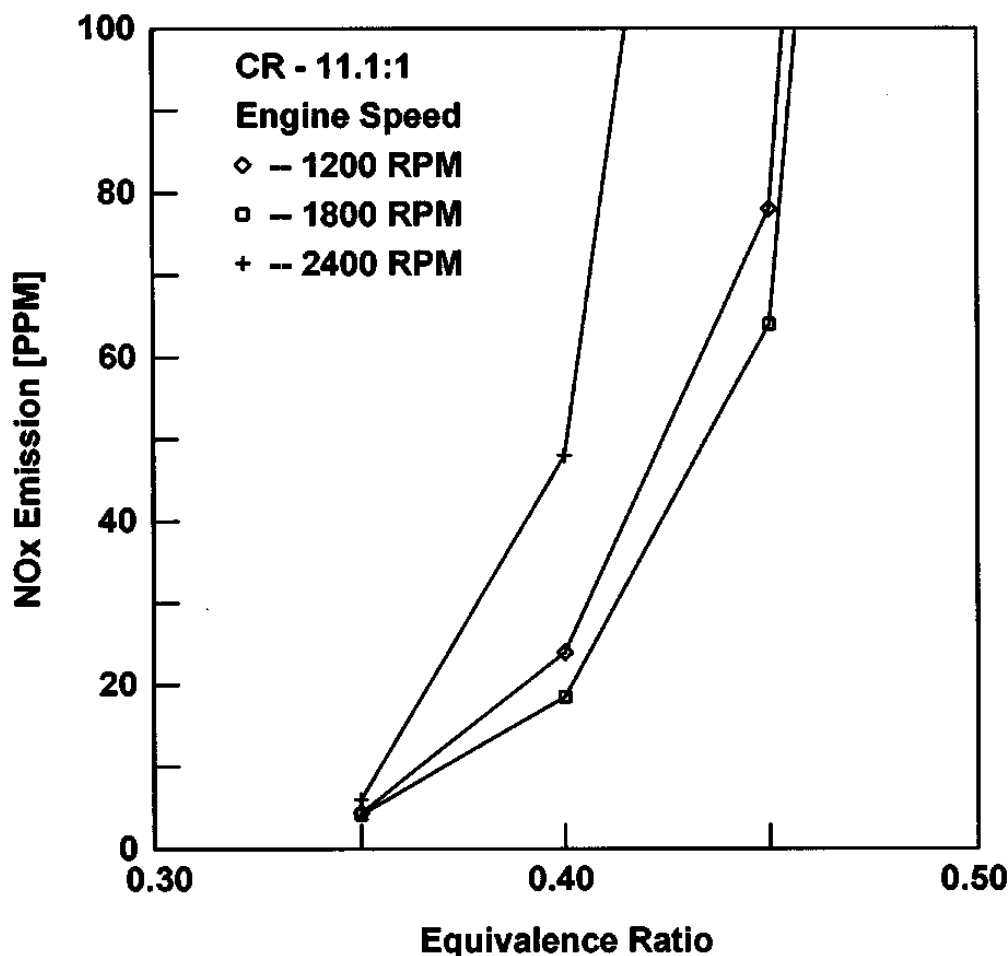# Combustion Research Facility News

NO$_x$ emission data verified in a hydrogen-fueled engine

Peter Van Blarigan and Bob Green, working closely with Ray Smith of Lawrence Livermore National Laboratory (LLNL), have measured the NO$_x$ emissions from a spark-ignition engine fueled with hydrogen. Data were taken as a function of equivalence ratio, compression ratio and engine speed, to validate the equivalence-ratio threshold at which the NO$_x$ emissions begin to increase substantially.

These measurements are a component of Sandia's ongoing program involved with hydrogen utilization in internal combustion engines. The main thrust of the program is the development of an engine optimized for hydrogen fuel for use in a series-hybrid, automotive propulsion system proposed by LLNL.

The engine required for this propulsion system is unique since it is envisioned to operate at a moderate speed and load (15 to 30 kW) while maximizing fuel efficiency and minimizing the tailpipe emissions. The expected emission levels are consistent with the ultra low emission vehicle standard. The NO$_x$ emission levels from a hydrogen-fueled vehicle using this propulsion system are expected to be consistent with those of a battery powered vehicle that is charged using electricity generated from a natural-gas fired power plant. The California Air Resources Board has already classified these electric cars as zero-emission vehicles.

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Measurements of NO$_x$ emission were taken in the exhaust of a single-cylinder research engine. Experiments were conducted by operating the engine in a lean premixed mode over a range of compression ratios, engine speeds and equivalence ratios.

It is clear from the data presented in the figure that NO$_x$ emissions as a function of equivalence ratio dramatically increase to unacceptable levels above an equivalence ratio of 0.40. At an equivalence ratio of 0.35, the measured NO$_x$ emissions were less than 10 ppm at all engine speeds and compression ratios considered.

These observations verify existing hydrogen-engine data that have been used to predict that an engine for a hydrogen-hybrid vehicle can be made to operate at extremely low NO$_x$ emission levels.

NO$_x$ emissions are shown as a function of equivalence ratio at three engine speeds for a compression ratio of 11.1:1.

# Team investigates mechanisms of NO$_X$ formation in industrial burner

Roger Farrow, Phil Paul, and David Rakestraw have been working with Professors Scott Samuelsen and Derek Dunn-Rankin and a team of four graduate students (Matt Miyasato, John Garman, David St. John, and Suresh Vilayanur) of the University of California, Irvine, to develop design criteria for ultra low NO$_X$ industrial burners that maintain high combustion efficiency at a relatively low cost.

The project, funded by the California Institute for Energy Efficiency (CIEE), the Southern California Gas Company, and the DOE Office of Basic Energy Sciences, also includes a team of combustion modelers from Lawrence Livermore National Laboratory.

Beginning with the design and fabrication of a 100,000 Btu/hr model industrial burner with full optical access (sited at the U.C. Irvine Combustion Laboratory), the teams have performed measurements of the aerodynamic, thermal, and chemical properties of the burner and compared these with detailed combustion calculations to gain a better understanding of the factors controlling efficient operation and low NO$_X$ emissions. A main goal of the project is to use this knowledge to develop an active control methodology for high-efficiency, low-NO$_X$ burner operation in practical systems.

> …regions of high NO concentration do not correlate with regions of high mean temperature in this part of the flame…

The Sandia team is helping to implement advanced laser diagnostics for *in-situ* measurements of temperature and NO concentration, consisting of coherent anti-Stokes Raman spectroscopy (CARS), laser-induced fluorescence (LIF), and degenerate four-wave mixing. From a matrix of
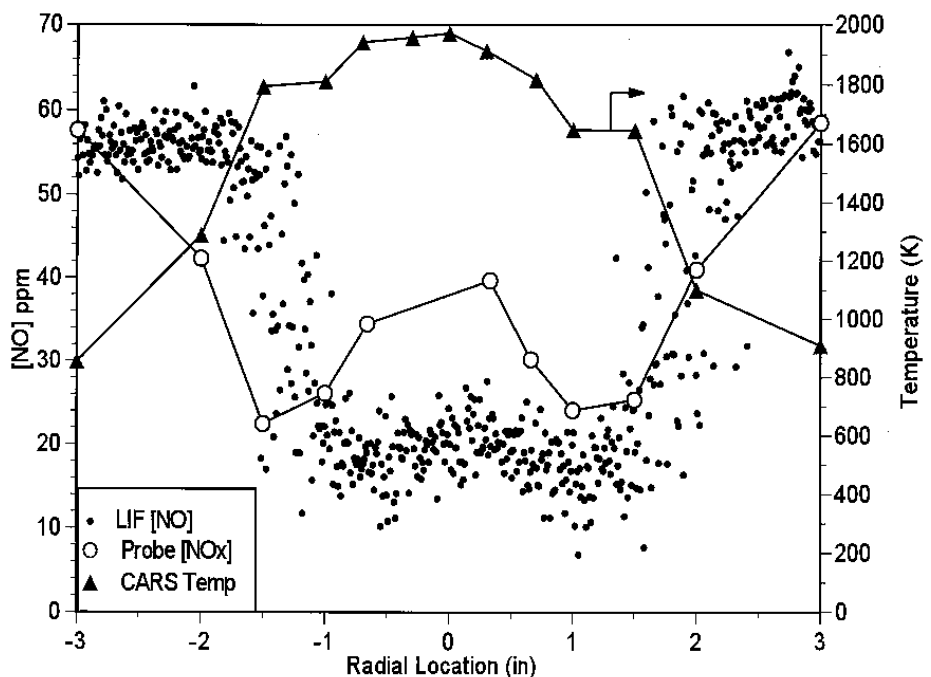
Temperature and NOx concentration measurements in a 100,000 Btu/hr model industrial burner at the UCI Combustion Laboratory. The nozzle is a counter-swirl type and the burner is operated with 5% excess air. The LIF concentration measurements are put on an absolute basis by matching the sampling probe measurements at the boundaries.

operating and boundary conditions involving varying the nozzle design, degree of swirl, excess air, and total gas flow rate, interesting sets of conditions were identified that produced either very high or very low NO$_X$ concentrations as measured with a chemiluminescent probe in the stack gases. These conditions were then investigated in detail using *in-situ* diagnostics to obtain time-averaged and single-pulse spatial maps of flow velocity (from laser Doppler anemometry), temperature (from multiplex CARS), turbulence intensity (from laser Raleigh scattering), and NO concentration (from LIF, planar LIF, and gas sampling).

An example of recent results is shown in the figure. Measurements were performed 0.5 inches above the burner surface along a diameter, using conditions that produced high NO emissions. Mean temperature data obtained from single-pulse CARS measurements are indicated by triangles, the filled circles indicate single-pulse LIF measurements of relative

NO concentration, and the open circles indicate time-averaged sampling probe measurements of NO$_X$ concentration. It is clear that the regions of high NO concentration do not correlate with regions of high mean temperature in this part of the flame, implying the existence of a significant transport mechanism.

Planar LIF images of NO and OH have also been obtained and are proving very useful in understanding the dynamics of this burner. These results have motivated further experiments to investigate the regions closer to the nozzle (within the quarl) where it is believed much of the NO is generated. ♨

Advisory Board meets

The Combustion Research Facility Advisory Board met in November to discuss activities, issues, and future directions. In the picture are members of the Advisory Board and Sandians who met with them. Seated are Bob Sawyer (University of California at Berkeley), John Rackley (Babcock & Wilcox), Mike Ingham (Chevron Research & Technology), Pat Flynn (Cummins Engine Company), John Maulbetsch (Electric Power Research Institute), and Howard Palmer (Pennsylvania State University). Standing are Bill McLean, Don Hardesty, John Crawford, Adel Sarofim (Massachusetts Institute of Technology), Jay Keller, Chuck Hartwig, and Larry Rahn.

Visitors

Professor Bob Bilger (University of Sydney), right, visited Rob Barlow in July to work out details of a collaborative experiment on bluff-body-stabilized flames planned for later this year. In the background is an enlarged photograph of the piloted jet flame burner that has been used extensively in the Turbulent Diffusion Flame laboratory and in Sydney for studies of turbulence-chemistry interactions.

Jon Nunes (left), a graduate student of Professor William Tong of the University of California at San Diego, was a visiting researcher this summer, working with David Chandler (right) and Larry Rahn on a project to develop a new laser-based technique for the determination of the chirality of a liquid-phase sample.

Basic oxygen furnace off-gas probed during steelmaking

A team comprising Dave Ottesen, Sarah Allendorf, Don Hardesty, Howard Johnsen, Bill Kent, and Jason Wang has been working with Bethlehem Steel to develop gas-phase optical diagnostics for control of basic oxygen steelmaking (see *CRF News*, **14**:4, 1992.) This project is supported by the DOE and the American Iron and Steel Institute.

The basic oxygen furnace (BOF) converts molten iron and scrap metal into steel in a batch process that oxidizes carbon and impurities with a high velocity jet of oxygen. The development of optical sensors for commercial steelmaking offers the possibility of real-time process control in hostile, high-temperature environments by means of remote, non-contacting measurements. Current BOF control technology relies on a materials balance for calculating the necessary quantities of reactants and processing times. Along with Bob Hurt and Beth Fuchs, the team is developing novel optical sensors that are designed to provide real-time, on-line analysis of the off-gases and melt phase.

Through laboratory work and pilot-scale experiments using a two-ton BOF facility at Bethlehem's Homer Research Laboratory, the team is evaluating two line-of-sight optical techniques for determining the concentration and temperature of infared-active gases (CO, CO_2, H_2O) in the BOF off-gas. One approach involves tunable diode laser (TDL) absorption spectroscopy. By monitoring the relative intensities of the absorption features over the course of the heat, we measure temperature and CO concentration along the laser line-of-sight.

The figure presents a typical gas-phase absorption spectrum during BOF oxygen blowing (solid line), and a calculated CO absorption spectrum (dashed line). Very good agreement is obtained for CO hot-band lines for a calculated temperature of 2125°F (1435 K) and concentration of 12%. In this wavelength region, CO accounts for most of the absorption features, but one particularly strong CO_2 feature is indicated in the figure. The ratio of CO to CO_2 is expected to be an indication of the completeness of decarburization. This technique enables accurate monitoring of the gas-phase temperature and CO/CO_2 ratio during the heat. This information will be used for both endpoint determination and process control.

A second line-of-sight approach involves the measurement of emission from infrared-active gas species. The optics of a spectrometer are focused on the cool oxygen lance to enhance the spectral contrast of the gas-phase emitters and to limit the optical pathlength. The resulting spectra are monitored during the heat. The intensity of the different molecular emission lines will ultimately be used to calculate temperatures and concentrations in a fashion analogous to the results for the TDL absorption sensor described above.
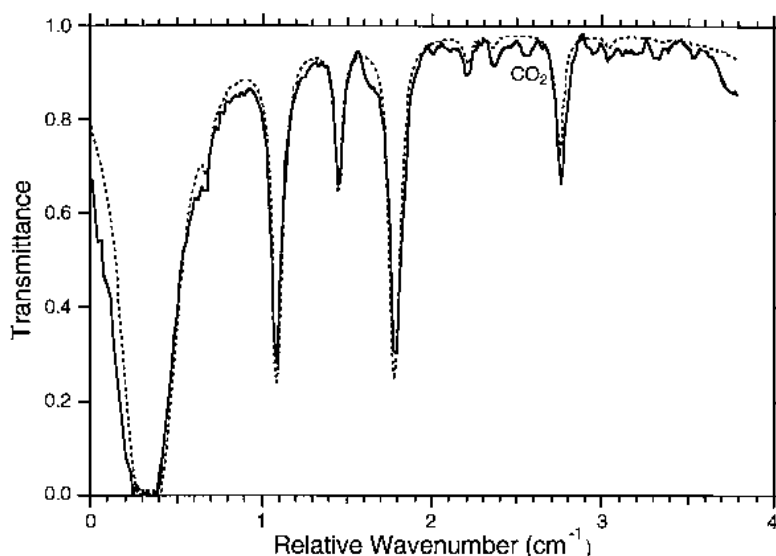
Plot of measured transmittance (solid curve) of tunable diode laser through off-gas of pilot-scale BOF. Comparison with CO transmittance spectrum calculated at 1435 K (dashed curve) indicates the off-gas is predominantly CO with lesser amounts of CO_2 and H_2O.

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